Large test to study the role of soil-air interaction in soil cracking

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ABSTRACT: Soil surfaces in contact with the atmosphere are interfaces where different processes play an important role in triggering the formation of cracks due to desiccation. Empirical evidence shows that variables such as solar radiation, wind speed or relative humidity have an impact on the amount of soil water evaporation. To study this subject, a new large-scale test facility has been built in the field, consisting of a 3×3×0.5 m (4.5 m^3) container filled with silty clay soil. There are internal sensors embedded in the specimen, and external sensors to collect measurements from natural conditions. The field experiment had duration of one year including all seasons. The specimen was continuously monitored with a digital camera, recording automatically images of the ground surface that were later used to analyze the crack pattern evolution using image analysis techniques. This paper presents some results from collected data in natural conditions including soil and air variables that will contribute to the understanding of crack formation and propagation in soils under changes of environmental conditions. The analysis of the results provides insight on the boundary effects in the cracking process and the role that the soil-air interaction plays in this process.

1 INTRODUCTION

Crack formation in soils due to the changes of environmental variables is a critical issue demanding much attention especially in relevant cases such as earth dams, waste reservoirs or agricultural applications. The response of the cracks to the variations of moisture may be seasonal, but also depends on environmental conditions that are typical in Mediterranean climates, i.e. drought periods followed by rainy events or floods.

Environmental variables as wind velocity, air relative humidity or solar radiation have a strong influence on the evaporation and infiltration of water through the soil surface which in addition to soil properties and mechanical boundary conditions define the evolution and patterns of desiccation cracks (Blight 1997, Cui et al. 2005, Shokri et al. 2015, among others). When comparing cracking experiments carried out under laboratory conditions with measurements of cracking evolution in the field, it becomes evident that the variables indicated above play a fundamental role in this phenomenon, which complicates any comparison in quantitative terms (Ledesma 2016, Cordero et al. 2016, Lakshmikantha 2009). That reason justifies the development of soil desiccation tests in the field. Obviously, it is not possible to apply in that case controlled boundary conditions; however, an effort is required to explore the quantitative effect of the environmental variables on soil desiccation and cracking.

This paper presents a large field test designed to analyze the relationship between environmental actions and soil cracking. It includes a description of the installation and the main variables measured during the duration of the test, which was planned for 1 year to include different weather conditions. The paper focuses on a few variables because of space constraints. Desiccation is produced after water evaporation from soil surface and measurements indicate that the effect of wind speed and solar radiation on evaporation rate is significant. The final purpose of this study is to identify the role of soil-air interaction in the context of soil desiccation and cracking.

2 DESCRIPTION OF THE TEST

2.1 *Setup of the field test*

The field test consisted of a large-scale soil specimen exposed to real atmospheric conditions. The soil specimen involves a volume of 4.5 m^3 cast into a 3×3×0.5 m container over a steel structure attached to four load cells resting on a reinforced concrete foundation slab (see Figure 1).

The setup is in the “Agropolis” site at Viladecans (Catalonia-Spain) near Barcelona airport in an area surrounded by farms and crops, which is a scientifictechnical unit that provides services to research groups of UPC - BarcelonaTech.

To monitor the main physical variables involved in soil cracking due to environmental conditions the specimen is instrumented internally with several types of sensors. Besides, other instruments located outside the soil specimen were used to measure atmospheric variables. All sensors installed in the soil mass or externally to the container were monitored automatically using a data logger Campbell CR1000 with a programmed code.

Figure 1. Overview of the field test. (1) Load cells; (2) Data recording system; (3) Anemometer; (4) VP3 sensors; (5) Digital camera; (6) IR120 sensor; (7) RSLab reflectometer.

2.1.1 *Aerial sensors*

Figure 1 shows the overview of the field test highlighting with numbers the external sensors, not in direct contact with the soil mass.

Number 1 represents four load cells acting as a scale measuring the weight of the soil specimen. In this manner we record the weight loss by drying or weight gain by wetting under natural conditions, which allows calculating the gravimetric moisture content and obtaining the evaporation rate. Number 2 refers to an external weatherproof box attached to the specimen site including the electronic connections of the sensors to the datalogger and the datalogger itself for the automatic collection data. Number 3 in Figure 1 is a Davis Cup Anemometer used to measure the direction and velocity of the wind at 10 cm above the specimen surface. Number 4 refers to two VP3 Decagon sensors at 2 and 10 cm above the specimen surface to monitor vapour pressure, temperature and relative humidity at the same place. Number 5 is a digital camera programmed to take a picture every hour, used to record images showing changes of the specimen's surface. Number 6 is an infrared remote thermometer placed 3 m high to measure the temperature at a point on the soil surface without contact with the object. Number 7 is the reflectometer installed as a test trial by the RSLab research group of the Department of Signal Theory and Communication of the UPC to indirectly determine the volumetric water content in the soil specimen by remote sensing techniques. Unfortunately, the configuration of the field test was inadequate to estimate the values accurately as intended with this instrument.

As shown in Figure 1 there is a weather station, belonging to Meteocat (Catalan Meteorological Service), located at 1.5 km from the experiment site, which provides the following data: rainfall, global solar radiation, wind speed and its direction, air temperature and air relative humidity at 2 m above the ground surface.

2.1.2 *Soil mass sensors*

Inside the soil specimen, there are three types of sensors: MPS6 Decagon, 5TE Decagon, and HFP01SC Hukseflux. Figure 2a shows the internal sensors at different depths, in particular, 10 cm, 15 cm, 25 cm and 40 cm, at selected points.

S1-S8 are eight MPS6 sensors to measure the matrix suction indirectly using the Frequency Domain Reflectometry (FDR) technique and a porous ceramic stone of known water retention curve.

T1-T3 are three 5TE sensors to monitor volumetric water content using FDR technique, and a thermistor to measure temperature, while two small stainless steel electrodes fixed in the sensor are used to obtain electrical conductivity.

For the appropriate spatial average, the field test is equipped with two HFP01SC sensors to measure the heat flux in the soil on a local scale using a thermopile measuring the temperature gradient across the plate (F1-F2), placed at 10 cm deep.

2.2 *Soil used in the field test*

The soil used in the present investigation was obtained from the Agropolis site, where the field test is installed.

The natural soil has a substantial amount of sand and silt sizes, although its geotechnical classification is a low plasticity clay (CL), likely due to almost 10% of clayey components. Results from the sieve and hydrometer analysis, pycnometer and Atterberg limits are shown in Table 1.

Table 1. Summary of measured properties of the soil used.

Index property	
Grain size distribution	
Sand content (≤ 2 mm, %)	48.3
Silt content (≤ 63 μm, %)	42.1
Clay content (≤ 2 μm, %)	9.6
Specific gravity	2.70
Atterberg limits	
Liquid limit (%)	28.9
Plastic limit (%)	16.5
Shrinkage limit (%)	13.8
Unified soil classification system (USCS)	CL

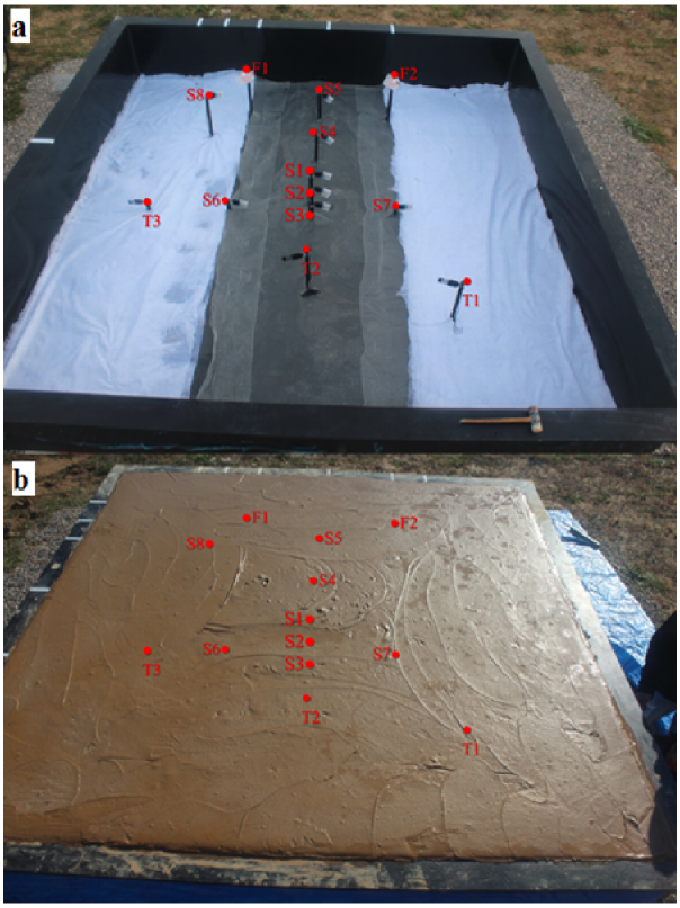

Figure 2. Distribution of the internal sensors. (S1-S8) Suction sensors; (T1-T3) VWC, temperature and EC; (F1-F2) Heat flux. **(a)** Container, geotextile & internal sensors. **(b)** Initiation of the test.

2.3 *Specimen preparation*

The preparation of the soil specimen was conducted using a rigorous protocol to obtain a material as homogeneous as possible. Also, sensors were checked and installed carefully in order to avoid a singular point in the soil mass, prone to crack initiation.

The field test started recording data on January 17, 2015 at 11 hours UTC, in winter 2014-2015. Prior to the initiation of the test, all sensors were checked Figure 2a shows a particular moment before filling the container when a pervious geotextile was installed on its bottom, to establish a limit with a well- defined boundary condition and to favor the equilibration of water pressures.

The natural soil from Agropolis was sieved to obtain soil particles with a diameter of less than 2 mm. The natural soil was collected with a bulldozer and sieved with 40 mm and 20 mm meshes. Subsequently, it was sieved through the 2-mm mesh and collected in bags. More than 4 m^3 of soil with particles smaller than 2 mm had to be processed in this way. The sieved material was then mixed with local water to make the slurry with an initial moisture content of about 45%. The slurry state was chosen for the initial soil state because it was easy to fill the container in this manner and the mixture was expected to be more homogeneous.

A 6-m^3 concrete mixer was used to mix the soil particles and water. With a gutter from the concrete mixer, the slurry was poured into the container. To eliminate vegetation during the test, an herbicide (GOAL Supreme®) was applied during placement of the slurry into the container. Figure 2b shows a picture of the container just after filling with the soil, the day when the test started.

Monitoring of the field experiment had duration of one year including all seasons. Most of installed sensors measured during the year except for sensors recording matrix suction and volumetric water content which reached their measurement range, either due to the intensity of the evaporation rate at the beginning of summer or because they became exposed to open atmosphere due to the cracks.

3 RESULTS OF MONITORING

A complete description of all measurements is out of the scope of this paper. Instead, some specific events and variables are described. Figure 3 shows for the initial 10 days, the hourly evaporation, E_r, computed from the container weight change by means of (1):

$$E_r \left[{}^{mm}\!/_{hour} \right] = -\frac{\Delta Weight\,[kg]}{9\,[m^2] \times 1\,[hour]} \tag{1}$$

assuming a water density of 1000 kg/m^3. A negative value for E_r represents a weight increment and eventually infiltration due to rainfall. Rainfall data is included in the Figure as well. Figure 4 presents the corresponding evolution of the water loss obtained from weight measurements for the same period.

Evaporation is the main issue creating soil shrinkage and eventually cracking. It is expected that environmental variables may control that evaporation and an effort was devoted to the measurement of those variables. Figure 5 shows the evolution of relative humidity in the air above the soil at different heights, and the wind speed also at two levels. It is important to point out that there is a gradient of relative humidity in the air, higher close to the soil surface because at the beginning of the experiment the soil was poured in a liquid consistency. Peaks of wind speed coincide with low values of relative humidity above the soil. Also, solar radiation (not shown here) affects relative humidity and temperature.

Figure 6 shows the crack pattern and the crack intensity factor, CIF (area of cracks over total area), evolution during the development of the test. Note that CIF increases continuously after cycles of desiccation and rainfall during the whole year, as cracking is not reversible when wetting the soil (Cordero et al, 2014).

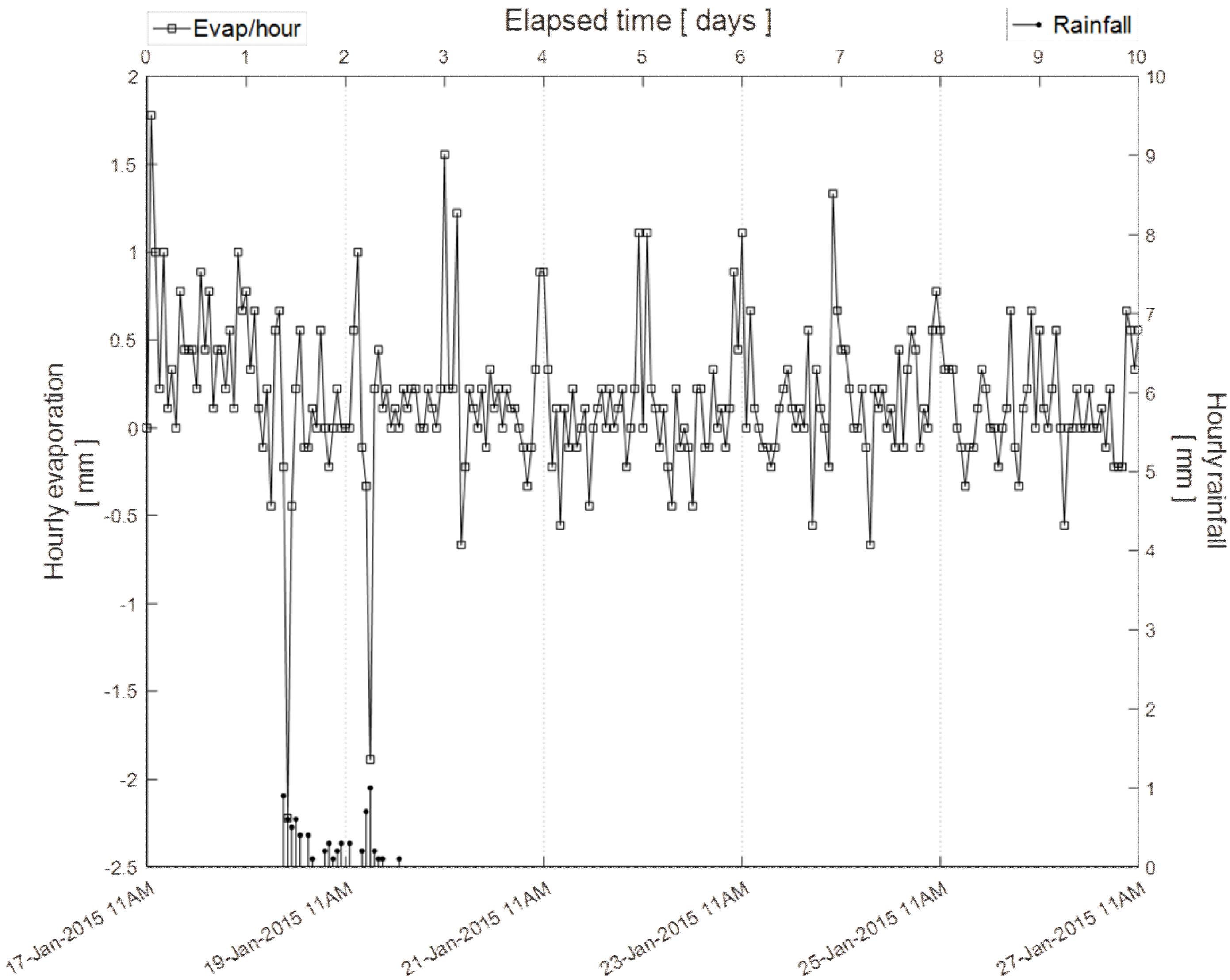

Figure 3. Evaporation rate in mm/hour and rainfall in mm for the initial 10 days of experiment.

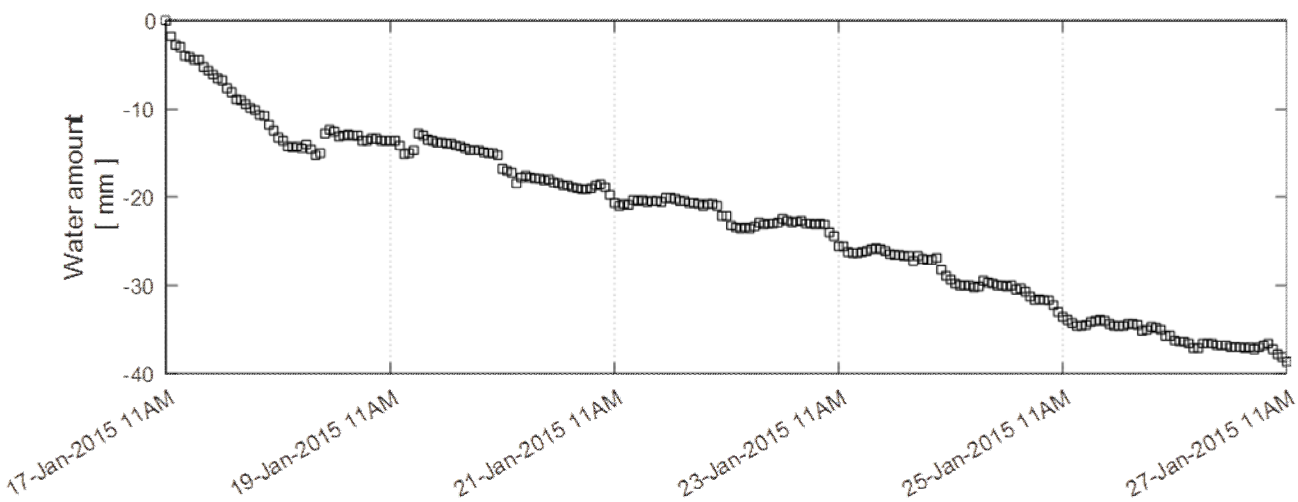

Figure 4. Water loss evolution during the first 10 days of experiment (in mm of water)

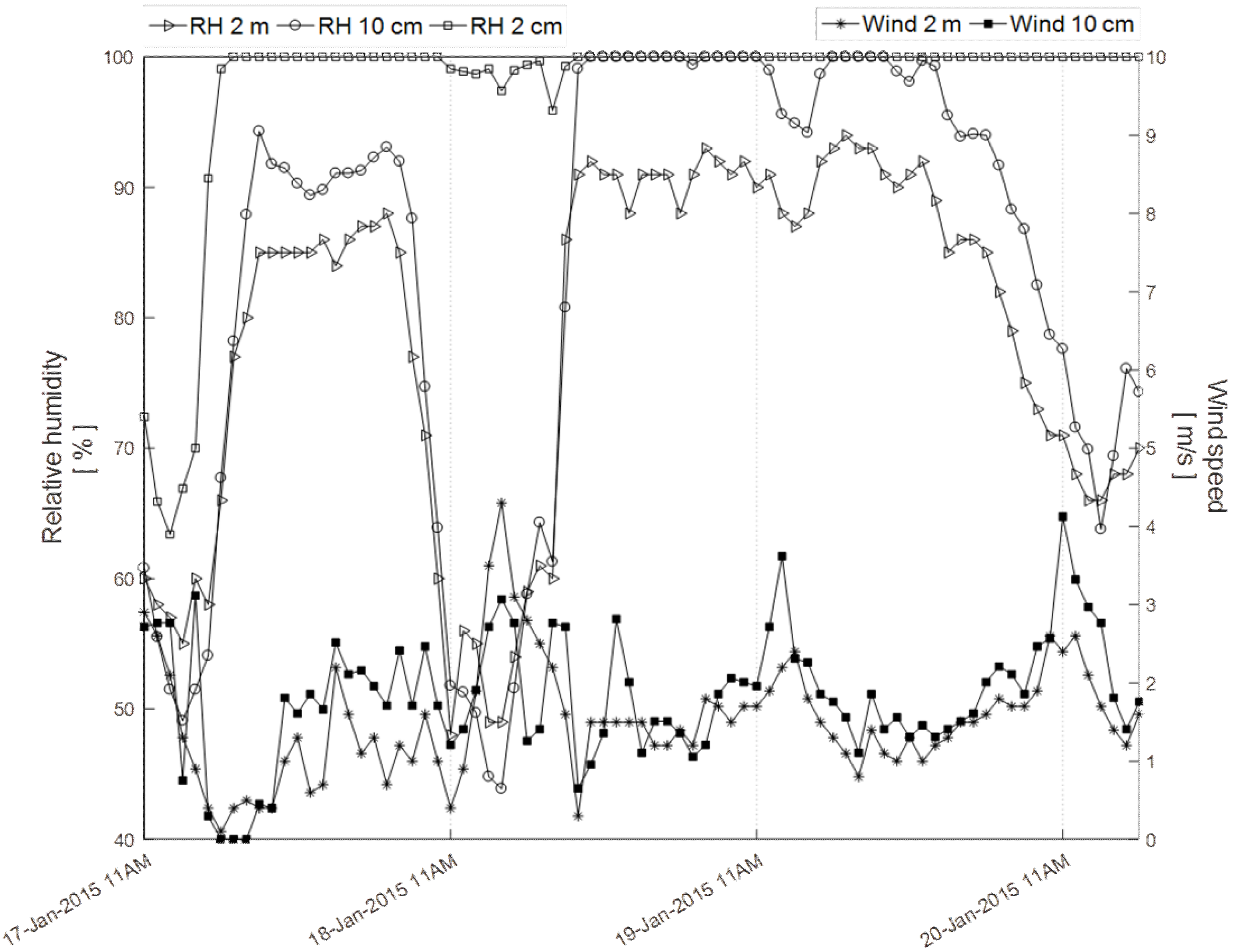

Figure 5. Relative humidity in the air at different heights above soil surface (2cm, 10 cm and 2 m) and wind speed at different heights above soil surface (10 cm and 2 m) for the 3 initial days.

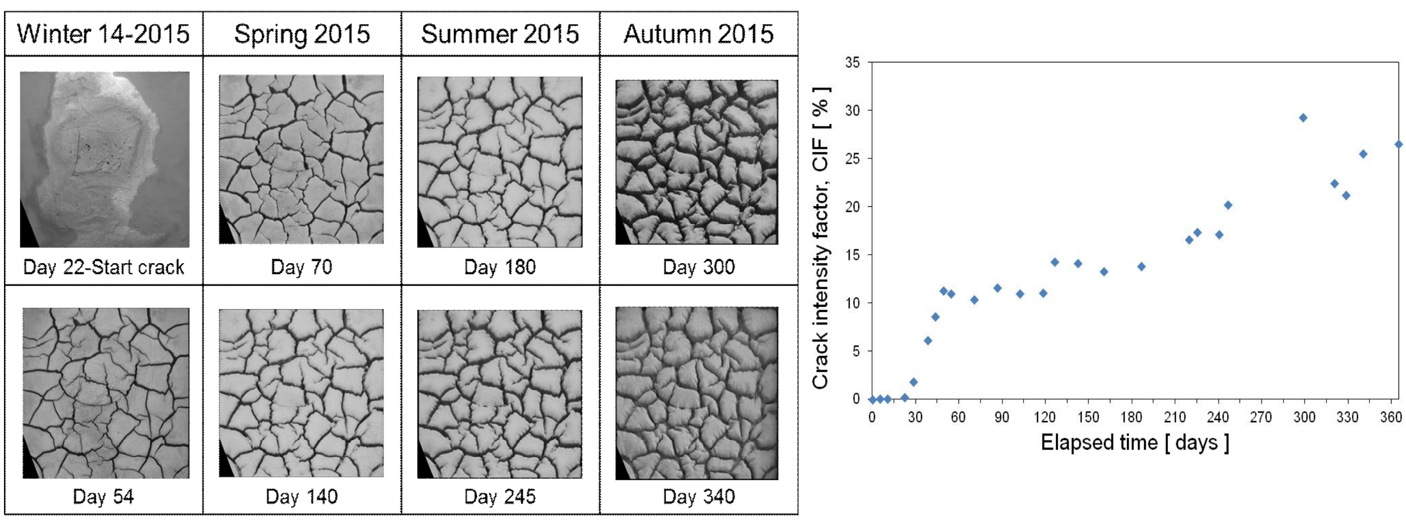

Figure 6. Cracks patterns at different elapsed days and evolution of the crack intensity factor obtained for the whole experiment.

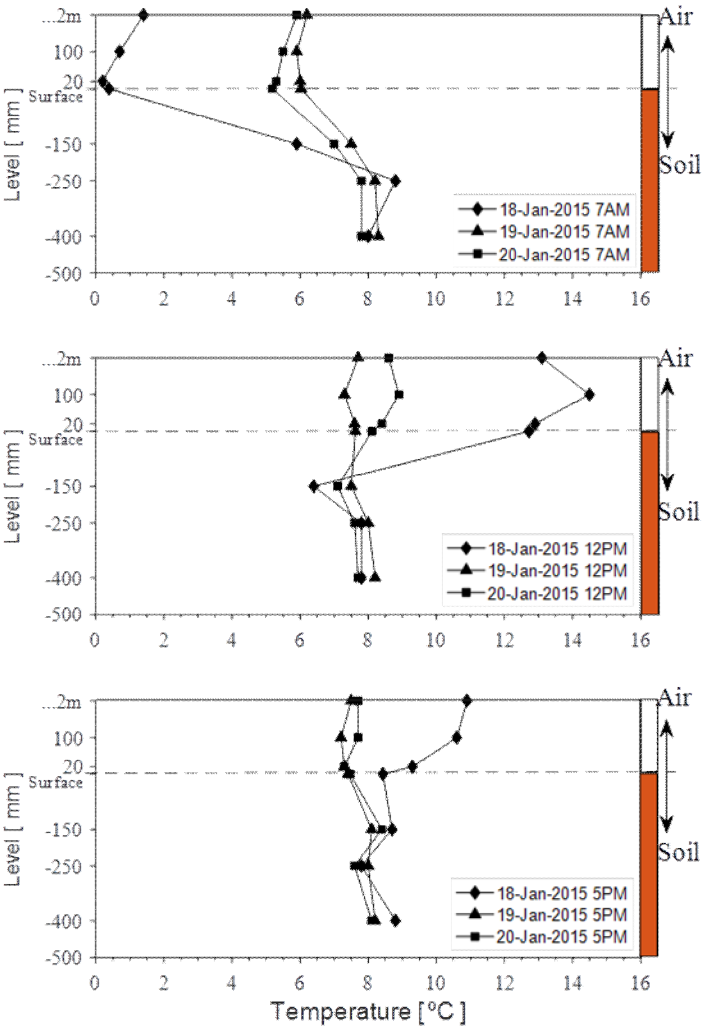

Figure 7. Temperature profiles above and below soil surface for 3 different days and at 3 different times.

One important feature of the measurements shown is the gradients of the variables involved around the soil surface. Figure 7 shows temperature profiles for 3 particular days at different times exhibiting those gradients. This is important when a numerical simulation is attempted. If only the soil mass is simulated, the boundary condition to apply on the soil surface cannot be the relative humidity, wind speed, solar radiation and temperature obtained from a meteorological station, as those data are measured at 2 m above soil surface. Correct atmospheric boundary conditions should take into account the behaviour of the soil-atmosphere interphase and that explains why most of the numerical approaches involve mathematical artefacts to calibrate boundary conditions (Wilson et al, 1994; Rodriguez et al, 2007).

4 CONCLUSIONS

A large scale field test involving a weighted container with desiccating soil under environmental conditions has been presented. Eventually, cracking develops depending on the main meteorological variables (i.e., solar radiation and wind velocity) as they control evaporation rates and therefore, soil shrinkage. Area of cracks progresses continuously in general, as wetting due to rainfall after a desiccating event does not reverse the cracking pattern. Measurements presented in the paper show that close to the soil surface there are important gradients of some variables, particularly relative humidity and temperatures suggesting water and heat flows not only in the soil mass, but also within the air. Wet air just above the soil surface is removed by wind, increasing the efficiency of the evaporation. Wind also removes heat, explaining temperature gradients close to the soil surface. Therefore, future numerical analyses should improve the simulation of the air above soil surface (maybe including atmospheric simulations) in order to evaluate the water and heat fluxes properly.

5 ACKNOWLEDGEMENTS

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